RESEARCH REPORT

18

Western Redcedar Site Index Models for the Interior of British Columbia

Gordon D. Nigh

2000

BRITISH COLUMBIA
Ministry of Forests
Research Program

103-06790/

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Canadian Cataloguing in Publication Data

Nigh, Gordon Donald, 1956-

Western redcedar site index models for the interior of British Columbia

(Research report ; 18)

Includes bibliographical references: p.

ISBN 0-7726-4101-3

1. Western redcedar - British Columbia – Growth. 2. Western redcedar - British Columbia – Growth - Mathematical models. 3. Site index (Forestry) - British Columbia. I. British Columbia. Ministry of Forests. Research Branch. II. Title. III. Series: Research report (British Columbia. Ministry of Forests. Research Branch) ; 18.

SD397.W46N53 2000 634.9'75628'09711 C00-960005-1

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Published by

Forestry Division Services Branch
Production Resources
722 Johnson Street, 4th Floor
Victoria, BC v8w 3E7

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ABSTRACT

Models are developed to predict top height, site index, and years to breast height for western redcedar (*Thuja plicata* Donn) on interior sites. Stem analysis and ecological data were collected from 46 plots in the Interior Cedar–Hemlock and Interior Douglas-fir biogeoclimatic zones. Four site trees were stem analyzed from each 0.04-ha plot. These data were converted into top height–breast height age, growth intercept, years to breast height, and site index data. A site index, growth intercept, and years to breast height model were then fit to the data. When faced with a choice of models, a graph of the models' relative accuracy assists in selecting the appropriate model.

ACKNOWLEDGEMENTS

I thank Bobby Love and Alison Burns, both from the B.C. Ministry of Forests, for help with the data collection. The data collection was funded by Forest Renewal BC. Review comments were provided by Dr. Val LeMay (University of British Columbia), and by John Pollack and Allen Banner (B.C. Ministry of Forests).

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INTRODUCTION

Until the mid-1990s, site index models (also known as height-age models) and years to breast height models were the mainstay for estimating site index and top height in British Columbia. Around that time, deficiencies in our ability to obtain good estimates of site index were noticed. For instance, the timber supply review identified the need for better site productivity (site index) information (B.C. Ministry of Forests 1996). Better site index information was required to write sound silviculture prescriptions and for generating yield tables for managed stands. Also, site classes (good, medium, poor, and low) in the inventory were converted into site indices. Therefore, a higher resolution for site index estimates was needed. Several initiatives were undertaken to mitigate these deficiencies. In 1993, the development of growth intercept models began, starting with the major species. These models estimate site index in juvenile stands and are well suited for silviculture applications. The Forest Productivity Council of British Columbia recommended that all site index models be tested, calibrated, or fit with British Columbia data, as some of the models were developed outside of British Columbia. This led to the analysis of existing stem analysis data and the collection and analysis of new data for site index and years to breast height modelling. Ecosystem-based estimates of site index, in which site index is ascertained from the biogeoclimatic ecosystem classification (BEC) site series (see Meidinger and Pojar 1991 for information about BEC), were available for some local areas. Additional data were compiled, leading to preliminary estimates of site index by site series (B.C. Ministry of Forests 1997).

As a result of these initiatives, many different models became available and guidelines were needed to select the most appropriate model. A first attempt at producing model selection guidelines was made for western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) in the interior of British Columbia (Nigh 1998).

The system of models produced for western hemlock enable the estimation of site index and top height for virtually any stand condition (Nigh 1998). This system consists of the following models:

- Site index: estimate top height from site index and breast height age, or site index from height and breast height age.
- Growth intercept: estimate site index from juvenile height growth.
- Site index–biogeoclimatic ecosystem classification (SIBEC): estimate site index from site series.
- Years to breast height: estimate the number of years it takes for top height trees to reach breast height (1.3 m).

Site index models estimate top height when the trees are above breast height. These models are also used to estimate site index, but their accuracy can be poor when estimating site index in young (< breast height age 20) and old (> breast height age 150) stands. Site index in stands between breast height ages 3 and 50 should be estimated with the growth intercept models. SIBEC site index estimates are derived without reference to the stand conditions and can be used for any site, provided the site series is known. Therefore, they are suited for estimating site index when other models are less accurate or are not applicable. The years to breast height models convert total age to breast height age and vice versa.

A system of models, similar to the ones for hemlock, is far from complete for western redcedar (*Thuja plicata* Donn) in the interior of British Columbia. Western redcedar is found in coastal and interior regions of British Columbia. In the interior, it occurs mainly in the Interior Cedar–Hemlock (ICH) biogeoclimatic zone, but also in the Interior Douglas-fir (IDF), and is present but uncommon in the Englemann Spruce–Subalpine Fir (ESSF) and Montane Spruce (MS) zones (Watts 1983; Meidinger and Pojar 1991). Redcedar is very shade tolerant, often grows in mixed species stands, and can be long-lived (Burns and Honkala 1990). In 1996/97, about 3% of the total volume harvested in the interior of British Columbia was redcedar (B.C. Ministry of Forests 1998). However, it is locally more important in the Nelson and Kamloops forest regions, where it represents 10% and 5% of the total volume harvested, respectively. Redcedar is also abundant in the Prince Rupert Forest Region, where it constitutes approximately 3% of the total volume harvested.

The site index curves and years to breast height models that were developed for cedar on the coast are being applied in the

interior (Thrower et al. 1994). This is done out of necessity, since curves for interior cedar are not available. Growth intercept models have not been developed for either the coastal or interior ranges of redcedar; however, some SIBEC estimates of western redcedar site index have been published (B.C. Ministry of Forests 1997).

This report outlines the development of a system of models to obtain good estimates of site index, height, and years to breast height for interior western redcedar. The project generated site index, growth intercept, and years to breast height models, and supplemented the SIBEC database with western redcedar data.

DATA

Fifty circular 0.04 ha stem analysis plots were established in stands containing western redcedar. Twenty-five of these plots were located in the ICHmc2 biogeoclimatic zone; the remainder of the plots were located in the ICHdw, ICHmw2, ICHmw3, ICHwk1, and IDFmw2 zones in the Nelson and Kamloops forest regions. Forest Productivity Council of British Columbia (1998) criteria were used to locate potential sampling sites and sample trees. The sites were found in stands that were:

- even-aged (ages of the trees in the main canopy are in a 20-year range);
- single-layered;
- moderately dense; and
- ecologically uniform (i.e., wholly contained in one site series).

The stands should be at least 80 years old, but preferably should be over 100 years old and contain four site (sample) trees. In addition, the stands chosen were not the result of previous partial cutting regimes and were located at least 50 m from major disturbances (e.g., roads, harvested areas). Furthermore, prospective stands were unaffected by non-site factors that might influence site index (e.g., fertilization, repression, heavy pruning).

In each plot, sample trees were selected by identifying the

four largest-diameter (at breast height) western redcedar trees. These trees were then checked for past damage, suppression, crown class, and vigour. Only trees that are growing at the potential of the site are suitable. Therefore, the trees must be (Forest Productivity Council of British Columbia 1998):

- dominant or co-dominant;
- straight stemmed and free of disease, damage, or breakage;
- free of suppression above breast height; and
- vigorous with a full crown.

Open-grown, veteran, or wolf trees are not acceptable for sampling.

The sample trees were felled and a section of the stem was taken at stump height (0.3 m), at breast height (1.3 m), and at 19 equally spaced locations along the stem between breast height and the top of the tree. The annual growth rings on each section were counted.

The outside bark diameter at breast height, the species, and the crown class of all plot trees greater than 2 cm in diameter were assessed. A full ecosystem description was also recorded (Luttmerding et al. 1990).

Each of the three models developed in this project have different data requirements, which are described below. The number of sample plots in each site series is small except for the ICHmc2/01. This limits the usefulness of the SIBEC data from this project and precludes the development of a SIBEC model. However, the data will be added to the SIBEC database and hence the information will be incorporated into the next version of the provincial SIBEC model.

SITE INDEX MODEL DATA

The stem analysis data were converted into tree height–breast height age data by removing stem analysis bias (Newberry 1991) and linearly interpolating heights between the sectioning points. The heights of the sample trees in each plot were averaged by breast height age, resulting in a set of top height–breast height age data for each plot. The top height at breast height age 50 is the site index of the plot. The height trajectories of the individual trees in the plot and the top height trajectories were plotted to detect anomalous height growth patterns in the

trees. Anomalous growth is usually caused by suppression at young ages or by top damage, and hence these trees are not suitable sample trees. Trees with aberrant growth habits were also not suitable. The top heights were re-calculated after eliminating unsuitable sample trees from the analysis. Four plots were deleted because of anomalous growth, leaving 46 plots for further analysis. Summary information about these plots is given in Table 1. Few plots with old trees were sampled because older trees are often decayed, or suppressed, or had some other defect that precluded their use as a site tree.

GROWTH INTERCEPT MODEL DATA

Growth intercept data were generated from the top height–breast height age data by using the following equation.

$$GI_{i,A} = \frac{H_{i,A} - 1.3}{A - A_{i,p}} \times 100, \qquad (1)$$

where: $GI_{i,A}$ = growth intercept (cm/yr) for plot i at age A;
$H_{i,A}$ = top height (m) of plot i at age A;
A = breast height age (A = 1, 2, 3, . . ., 50 yrs); and
$A_{i,p}$ = the proportion of height growth for plot i between breast height age 0 and 1 that occurred below breast height.

YEARS TO BREAST HEIGHT MODEL DATA

The number of years it takes trees to reach breast height was determined from the stem analysis data. Since the lowest stem section was taken at stump height, the time it took the trees to reach stump height was found by extrapolating the height growth between stump height and breast height back to the time of germination.

TABLE 1 *Summary information for the 46 sample plots*

Plot	Biogeoclimatic Ecosystem Classification					Site index (m)	Height (m)	Breast height age (yrs)
	Zone	Subzone/ variant	SMR[a]	SNR[b]	Site series			
3	ICH	mc2	F	C	52	18.03	28.39	83
7	ICH	mc2	F	C	01	16.55	22.42	76
9	ICH	mc2	F	C	01	18.15	23.72	72
10	ICH	mc2	SD	C	52	10.75	24.22	136
12	ICH	mc2	F	C	52	14.76	25.01	100
14	ICH	mc2	SD	C	52	18.28	24.48	80
19	ICH	mc2	F	D	53	17.57	26.60	84
24	ICH	mc2	SD	C	01	16.61	24.07	89
31	ICH	mc2	F	C	01	16.69	22.57	71
51	ICH	mc2	F	C	52	17.10	24.75	84
57	ICH	mc2	M	D	03	15.63	22.74	75
62	ICH	mc2	SD	C	01	15.68	19.70	82
69	ICH	mc2	F	C	01	12.33	27.03	120
75	ICH	mc2	F	C	01	16.59	19.91	67
80	ICH	mc2	SD	C	01b	13.64	24.12	103
97	ICH	mc2	F	C	01	15.61	24.13	94
116	ICH	mc2	F	D	03	14.31	18.50	69
201	ICH	mc2	F	C	01a	14.66	29.31	101
202	ICH	mc2	SD	C	01b	16.75	28.26	87
208	ICH	mc2	SD	C	01	16.43	19.65	72
212	ICH	mc2	M	D	03	14.08	19.97	73
217	ICH	mc2	SD	C	01	15.75	20.31	81
221	ICH	mc2	F	C	01a	11.55	28.10	146
1000	ICH	mc2	F	D	01a	13.64	18.78	71
2001	ICH	mw2	SD	C	04	15.78	26.50	101

TABLE 1 *Continued.*

Plot	Biogeoclimatic Ecosystem Classification					Site index (m)	Height (m)	Breast height age (yrs)
	Zone	Subzone/ variant	SMR[a]	SNR[b]	Site series			
2002	ICH	mw2	VM	D	06	20.14	26.99	76
2003	ICH	wk1	F	C	01	21.73	29.10	70
2004	ICH	mw3	M	C	07	19.33	30.00	82
2005	ICH	mw2	F	B	01	16.15	26.51	107
2006	ICH	mw2	F	B	01	17.94	31.43	87
2007	ICH	mw2	SD	B	04	19.55	27.74	84
2008	ICH	dw	F	C	01b	12.78	27.23	101
2009	ICH	dw	F	C	01b	15.04	24.51	108
2010	ICH	wk1	M	D	05	18.64	32.10	109
2011	ICH	wk1	F	B	01	19.77	27.16	72
2012	ICH	wk1	M	C	05	20.04	30.41	93
2013	ICH	wk1	VM	C	05	22.03	29.84	90
2014	ICH	mw3	F	B	04	17.77	31.71	100
2015	ICH	mw3	M	D	07	17.60	32.54	106
2016	IDF	mw2	MD	C	01-YC	10.50	20.70	105
2017	ICH	mw3	M	C	07	17.51	30.07	94
2018	ICH	mw3	F	C	06	23.89	33.54	89
2019	ICH	mw3	VM	C	08	18.38	27.07	110
2020	ICH	nw2	VM	D	05	22.39	31.97	84
2021	IDF	mw2	MD	B	01-YC	20.42	31.91	102
2025	ICH	mw3	SD	B	01	19.92	28.82	84

a SMR = soil moisture regime: MD = moderately dry; SD = slightly dry; F = fresh; M = moist; VM = very moist.

b SNR = soil nutrient regime: B = poor; C = medium; D = rich.

METHODS

SITE INDEX MODEL

Several model formulations (Kurucz 1978; Chen et al. 1998; Nigh 1998) were tested in a preliminary analysis to determine which formulation fit the data the best; that is, had the smallest mean square error. The log–logistic function (equation 2; Nigh 1998), which gave the smallest mean square error, was chosen for further analysis:

$$H_{i,A} = 1.3 + (SI_i - 1.3) \times \frac{a_1}{a_2} + \varepsilon_{i,A}, \quad (2)$$

where: SI_i = site index (m) of plot i;
a_1 = $1 + e^{b_0 + b_1 \times \ln(49.5) + b_2 \times \ln(SI_i - 1.3)}$;
a_2 = $1 + e^{b_0 + b_1 \times \ln(A - 0.5) + b_2 \times \ln(SI_i - 1.3)}$;
b_0, b_1, and b_2 = parameters; and
$\varepsilon_{i,A}$ = random error term for plot i at breast height age A.

Note that 0.5 is subtracted from the breast height ages to remove some stem analysis bias (Nigh 1995). To reduce serial correlation in the residuals ($\varepsilon_{i,A}$), equation 2 was converted into a height growth model, and an autoregressive model of order 1 [AR(1) model] with a 5-year lag was included as part of the error term (Nigh 1997a), resulting in:

$$Hg_{i,A} = -\frac{(SI_i - 1.3) \times a_1 \times (a_2 - 1) \times b_1}{a_2^2 \times (A - 0.5)} + \phi \times \omega_{i,A-5} + v_{i,A}, \quad (3)$$

where: $Hg_{i,A}$ = height growth (m/yr) of plot i at age A ($Hg_{i,A} = H_{i,A-0.5} - H_{i,A-0.5}$), with A = 3.5, 8.5, 13.5, …;
ϕ = first-order autocorrelation;
$\omega_{i,A-5}$ = error for plot i at age $A-5$; and
$v_{i,A}$ = random error term for plot i at breast height age A.

This model was fit to growth data using nonlinear least-squares regression. The Students t-test was used to determine whether the residuals had a mean of zero, and the Shapiro–Wilk's test was applied to test for normality (Shapiro and Wilk 1965).

Fit statistics such as R^2 and the mean square error are not very meaningful because the fitted model is a growth model and an AR(1) model was included in the error term. However, the site index model will be used to estimate height, so some indication of how well the model performs in its intended use is required. To do this, I used the site index model to estimate the top height of the plots at breast height ages 5, 10, 15, ..., excluding breast height age 50 because the model is conditioned to have no error at that age. I then calculated the error in each height estimate by subtracting the estimated height from the actual height.

GROWTH INTERCEPT MODEL

The growth intercept modelling technique in British Columbia has evolved to the point where it is now standard. The latest modifications to the technique (Nigh 1997b) were used in this project. The site index–growth intercept data were fit to equation 4 with nonlinear least-squares regression. A model was fit for breast height ages 1, 2, 3, ..., 50:

$$SI_i = 1.3 + b_0 \times GI_{i,A}^{b_1} + \varepsilon_i, \qquad (4)$$

where: b_0 and b_1 = parameters; and
ε_i = random error term for plot i.

Parameter b_0 was re-parameterized ($b_0 = e^{b'_0}$) before fitting to reduce the parameter-effects nonlinearity (Ratkowsky 1983).

Statistical tests were performed to ensure that the standard regression assumptions were met. The Students t-test was used to determine whether the residuals had a mean of zero, and the Shapiro–Wilk's test was applied to test for normality (Shapiro and Wilk 1965). The residuals were assumed to be independent, based on the sampling method. Tests specifically for nonlinear models were applied to detect parameter-effects and intrinsic nonlinearity and parameter bias (Ratkowsky 1983).

YEARS TO BREAST HEIGHT MODEL

The years to breast height–site index data were plotted to gain insight into an appropriate model function. Two outliers were

apparent and were deleted before analyzing the data. The graph of the data indicated that a simple linear model was appropriate to model the relationship between years to breast height and site index. The following equation was fit to the data.

$$YTBH_i = b_0 + b_1 \times SI_i + \varepsilon_i, \quad (5)$$

where: $YTBH_i$ = number of years it takes for plot i to reach breast height; and
b_0 and b_1 = parameters.

Statistical tests were performed to ensure that the standard regression assumptions were met. The Students t-test was used to determine whether the residuals had a mean of zero, and the Shapiro–Wilk's test was applied to test for normality (Shapiro and Wilk 1965). The observations were assumed to be independent because of the sampling design.

RELATIVE ACCURACY

The relative accuracy of the site index and growth intercept models was compared graphically. Relative accuracy was measured by the square root of the mean square error in the site index estimates from the models. For the site index model, the errors were calculated by subtracting the estimated site indices from the actual site indices using the same data that were used to fit the model. The mean square error of the growth intercept model was obtained directly from the regression analysis.

RESULTS

SITE INDEX MODEL

The parameter estimates (and associated standard errors) for the height growth model are: $b_0 = 9.474$ (0.4442), $b_1 = -1.340$ (0.02073), and $b_2 = -1.244$ (0.1587). These parameter estimates are used in the site index model (equation 2). There was evidence ($p < 0.001$) that the residuals were not normally distributed; however, a histogram showed that the residuals were close to being normal. The mean of the residuals was not

significantly different from zero. Although the non-normality in the residuals may invalidate the *t*-test results, this test is robust against moderate departures from normality (Montgomery 1984). The steps taken to reduce serial correlation were successful. The site index model is shown in equation 6 and is graphed in Figure 1.

$$H_A = 1.3 + (SI - 1.3) \times \frac{1 + e^{9.474 - 1.340 \times \ln(49.5) - 1.244 \times \ln(SI - 1.3)}}{1 + e^{9.474 - 1.340 \times \ln(A - 0.5) - 1.244 \times \ln(SI - 1.3)}} \quad (6)$$

Summary statistics on the errors in the height estimates from the site index model (Table 2) give some indication of the accuracy of the model.

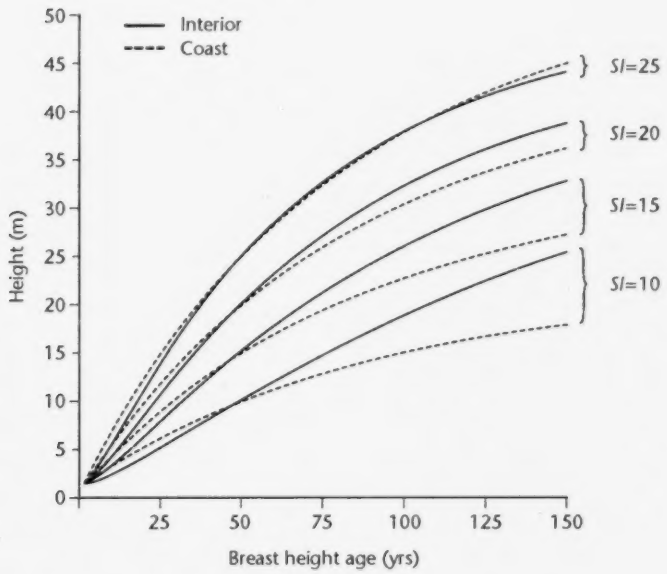

FIGURE 1 *Graph of the site index curves for interior and coastal western redcedar for site indices 10, 15, 20, and 25 m.*

TABLE 2 *Summary statistics on the errors in the height estimates for the site index model*

Breast height age (yrs)	Number of observations	Mean error (μ)	Standard deviation	t (H_0: $\mu = 0$)	p-value
All	770	0.011	1.0	0.31	0.75
5	46	0.20	0.25	5.5	0.00
10	46	0.083	0.49	1.2	0.25
15	46	-0.035	0.70	-0.34	0.74
20	46	-0.082	0.83	-0.67	0.50
25	46	-0.10	0.84	-0.83	0.41
30	46	-0.061	0.80	-0.52	0.61
35	46	-0.023	0.71	-0.22	0.82
40	46	-0.012	0.53	-0.16	0.88
45	46	-0.021	0.30	-0.47	0.64
55	46	-0.024	0.31	-0.52	0.61
60	46	-0.043	0.57	-0.51	0.61
65	46	-0.059	0.83	-0.49	0.63
70	44	-0.037	1.1	-0.23	0.82
75	37	-0.040	1.3	-0.19	0.85
80	34	-0.026	1.6	-0.093	0.93
85	24	0.23	1.8	0.63	0.53
90	20	0.098	1.9	0.24	0.82
95	16	0.30	2.0	0.60	0.56
100	16	0.29	2.2	0.54	0.60
105	9	-0.38	2.2	-0.51	0.62
110	4	-0.44	3.0	-0.29	0.79
115	3	1.0	1.1	1.6	0.24
120	3	0.93	1.0	1.5	0.26
125	2	0.39	1.1	0.53	0.69
130	2	0.27	1.1	0.34	0.79
135	2	0.17	1.2	0.20	0.87

GROWTH INTERCEPT MODEL

The results of the growth intercept modelling are presented in Table 3 for breast height ages 1, 5, 15, 25, 35, 45, and 50. A graph of the model and data for these ages is presented in Figure 2. The growth intercept models and their root mean square error for all ages are shown in Table 4. The residual analysis indicates that, for all ages, the mean of the residuals is not significantly different from zero, and the residuals are normally distributed with equal variances. As well, none of the growth intercept models showed evidence of significant intrinsic or parameter-effects nonlinearity or parameter bias (Ratkowsky 1983).

TABLE 3 *Results of the growth intercept model analysis for breast height ages 1, 5, 15, 25, 35, 45, and 50*

Breast height age (yrs)	Parameter	Estimate	Standard error
1	b_0'	1.320	0.1817
	b_1	0.4769	0.05903
5	b_0'	1.356	0.1872
	b_1	0.4432	0.05801
15	b_0'	1.115	0.1765
	b_1	0.4974	0.05235
25	b_0'	0.6015	0.1613
	b_1	0.6328	0.04648
35	b_0'	0.1012	0.1171
	b_1	0.7685	0.03332
45	b_0'	-0.4464	0.05074
	b_1	0.9254	0.01444
50	b_0'	-0.7043	0.005062
	b_1	1.001	0.001443

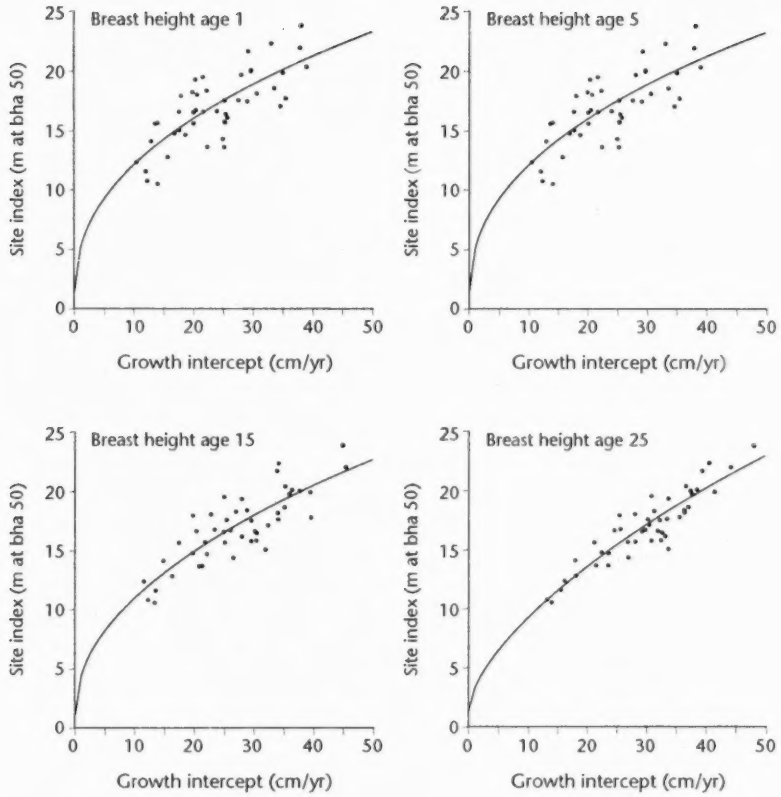

FIGURE 2 *Growth intercept models for breast height ages 1, 5, 15, 25, 35, 45, and 50 overlaid on the data points.*

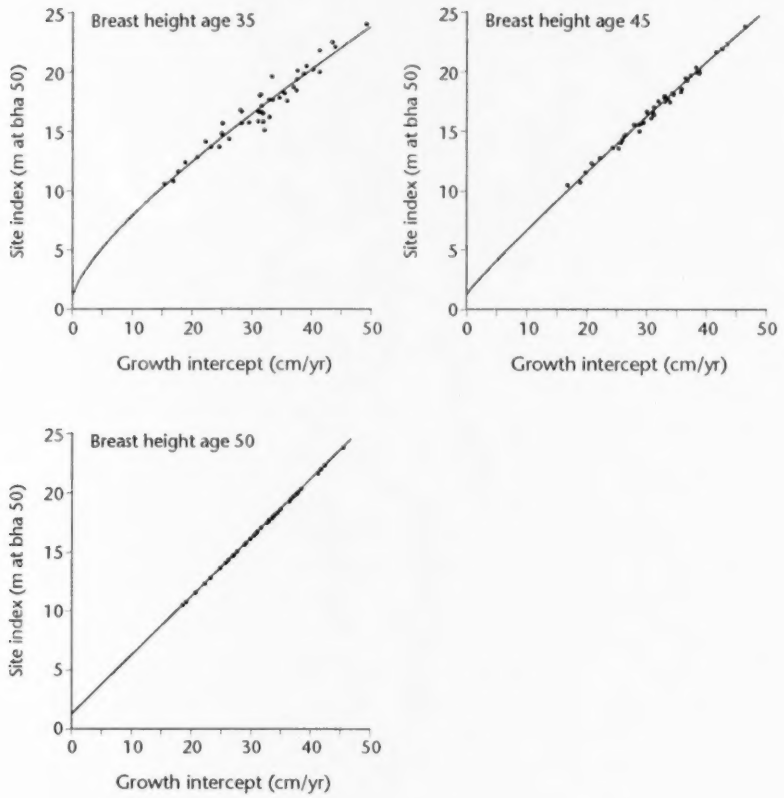
Breast height age 35
Site index (m at bha 50)
Growth intercept (cm/yr)
Breast height age 45
Site index (m at bha 50)
Growth intercept (cm/yr)
Breast height age 50
Site index (m at bha 50)
Growth intercept (cm/yr)

FIGURE 2 *Continued.*

TABLE 4 *Growth intercept models for breast height ages 1–50*

Breast height age (yrs)	Model	Root mean square error	Breast height age (yrs)	Model	Root mean square error
1	$\hat{SI}=1.3+3.744\times GI_{1}^{0.6769}$	1.912	26	$\hat{SI}=1.3+1.728\times GI_{26}^{0.6478}$	1.214
2	$\hat{SI}=1.3+4.123\times GI_{2}^{0.6281}$	1.985	27	$\hat{SI}=1.3+1.634\times GI_{27}^{0.6628}$	1.157
3	$\hat{SI}=1.3+4.117\times GI_{3}^{0.6252}$	2.000	28	$\hat{SI}=1.3+1.555\times GI_{28}^{0.6758}$	1.102
4	$\hat{SI}=1.3+3.922\times GI_{4}^{0.6402}$	1.967	29	$\hat{SI}=1.3+1.493\times GI_{29}^{0.6865}$	1.056
5	$\hat{SI}=1.3+3.882\times GI_{5}^{0.6432}$	1.955	30	$\hat{SI}=1.3+1.424\times GI_{30}^{0.6991}$	1.012
6	$\hat{SI}=1.3+3.889\times GI_{6}^{0.6414}$	1.945	31	$\hat{SI}=1.3+1.361\times GI_{31}^{0.7113}$	0.9795
7	$\hat{SI}=1.3+3.843\times GI_{7}^{0.6439}$	1.900	32	$\hat{SI}=1.3+1.292\times GI_{32}^{0.7255}$	0.9449
8	$\hat{SI}=1.3+3.697\times GI_{8}^{0.6530}$	1.856	33	$\hat{SI}=1.3+1.221\times GI_{33}^{0.7409}$	0.8973
9	$\hat{SI}=1.3+3.609\times GI_{9}^{0.6585}$	1.838	34	$\hat{SI}=1.3+1.160\times GI_{34}^{0.7552}$	0.8437
10	$\hat{SI}=1.3+3.522\times GI_{10}^{0.6636}$	1.812	35	$\hat{SI}=1.3+1.106\times GI_{35}^{0.7685}$	0.7928
11	$\hat{SI}=1.3+3.432\times GI_{11}^{0.6692}$	1.792	36	$\hat{SI}=1.3+1.057\times GI_{36}^{0.7814}$	0.7366
12	$\hat{SI}=1.3+3.332\times GI_{12}^{0.6764}$	1.763	37	$\hat{SI}=1.3+1.006\times GI_{37}^{0.7942}$	0.6837
13	$\hat{SI}=1.3+3.229\times GI_{13}^{0.6841}$	1.728	38	$\hat{SI}=1.3+0.9524\times GI_{38}^{0.8106}$	0.6350
14	$\hat{SI}=1.3+3.150\times GI_{14}^{0.6896}$	1.704	39	$\hat{SI}=1.3+0.8992\times GI_{39}^{0.8270}$	0.5851
15	$\hat{SI}=1.3+3.048\times GI_{15}^{0.6974}$	1.675	40	$\hat{SI}=1.3+0.8560\times GI_{40}^{0.8411}$	0.5369
16	$\hat{SI}=1.3+2.927\times GI_{16}^{0.7076}$	1.645	41	$\hat{SI}=1.3+0.8145\times GI_{41}^{0.8554}$	0.4925
17	$\hat{SI}=1.3+2.784\times GI_{17}^{0.7206}$	1.616	42	$\hat{SI}=1.3+0.7697\times GI_{42}^{0.8717}$	0.4473
18	$\hat{SI}=1.3+2.645\times GI_{18}^{0.7338}$	1.587	43	$\hat{SI}=1.3+0.7251\times GI_{43}^{0.8891}$	0.3997
19	$\hat{SI}=1.3+2.519\times GI_{19}^{0.7466}$	1.561	44	$\hat{SI}=1.3+0.6819\times GI_{44}^{0.9070}$	0.3504
20	$\hat{SI}=1.3+2.398\times GI_{20}^{0.7595}$	1.522	45	$\hat{SI}=1.3+0.6399\times GI_{45}^{0.9254}$	0.2976
21	$\hat{SI}=1.3+2.278\times GI_{21}^{0.7732}$	1.463	46	$\hat{SI}=1.3+0.5999\times GI_{46}^{0.9441}$	0.2433
22	$\hat{SI}=1.3+2.168\times GI_{22}^{0.7863}$	1.402	47	$\hat{SI}=1.3+0.5644\times GI_{47}^{0.9617}$	0.1770
23	$\hat{SI}=1.3+2.050\times GI_{23}^{0.8013}$	1.345	48	$\hat{SI}=1.3+0.5385\times GI_{48}^{0.9754}$	0.1116
24	$\hat{SI}=1.3+1.934\times GI_{24}^{0.8170}$	1.296	49	$\hat{SI}=1.3+0.5168\times GI_{49}^{0.9877}$	0.05825
25	$\hat{SI}=1.3+1.825\times GI_{25}^{0.8328}$	1.255	50	$\hat{SI}=1.3+0.4945\times GI_{50}^{1.001}$	0.02780

YEARS TO BREAST HEIGHT MODEL

The parameter estimates (and associated standard errors) for the years to breast height model are $b_0 = 18.18$ (1.583) and $b_1 = -0.5526$ (0.09224). The model and data are plotted in Figure 3. The residual analysis indicates that the standard regression assumptions hold. The years to breast height model is:

$$YTBH = 18.18 - 0.5526 \times SI. \tag{7}$$

This model accurately (the root mean square error is 1.86 years) estimates the number of years it takes for the trees to reach breast height from germination.

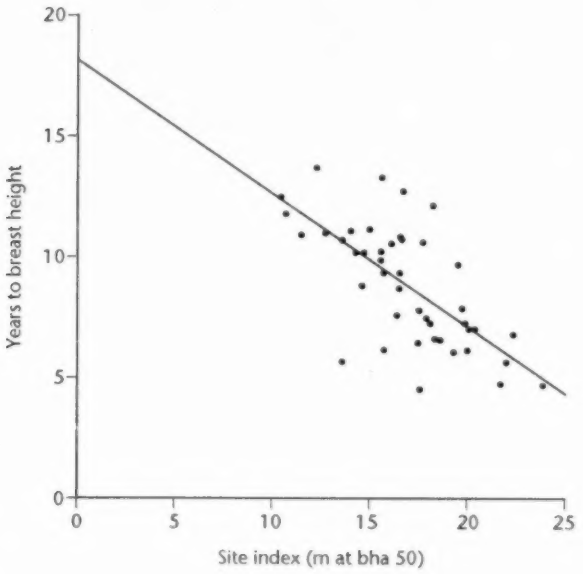

FIGURE 3 *Years to breast height model overlaid on the data points.*

DISCUSSION

This research makes height growth and site index information available for western redcedar in the interior of British Columbia. This information is important in many areas of forest management, including formulating silviculture prescriptions, generating yield tables for timber supply analyses, and determining green-up ages. Top height estimates are obtained from the new site index model. Site index can be estimated from either the site index or growth intercept model. The years to breast height model estimates the number of years it takes for the trees to reach breast height for different site index values. This model converts breast height age to total age and vice versa, and is also an integral part of the interpolation process for estimating heights below breast height.

The site index, growth intercept, and years to breast height models are accurate. The root mean square error for the site index model is approximately 1.0 m. In contrast, the root mean square error is 0.97 for lodgepole pine (*Pinus contorta* var. *latifolia*),[1] 1.02 for interior spruce (*Picea glauca*),[2] 0.85 for interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) (Thrower and Goudie 1992), and 0.94 for interior western hemlock (Nigh 1998).

The accuracy of the western redcedar growth intercept models are also good, relative to those for other species. The growth intercept models are less accurate than those for lodgepole pine (Nigh 1997c), but are more accurate than those for interior spruce (Nigh 1999), western hemlock (Nigh 1998), Douglas-fir (Nigh 1997d), and subalpine fir (*Abies lasiocarpa*).[3]

The root mean square error of the western redcedar years to breast height model is approximately 1.9 years, which makes it reasonably accurate. For comparison, the root mean square error for the interior western hemlock years to breast height model is 2.8 years (Nigh 1998).

The site index model for interior western redcedar is quite different from the model for coastal redcedar in the CWH biogeoclimatic zone (Kurucz 1978), particularly at low site indices. Figure 1 shows the coastal and interior models for site indices 10, 15, 20, and 25 m. The interior models have lower heights below breast height age 50 and higher heights above breast height age 50 for site indices 10, 15, and 20 m. The differences in height are substantial at older ages, leading me to suspect

1 J.S. Thrower and Associates Ltd. 1994. Revised height-age curves for lodgepole pine and interior spruce in British Columbia. B.C. Min. For., Res. Br., Victoria, B.C. Unpubl. rep.

2 Ibid.

3 J.S. Thrower and Associates Ltd. 1997. Development of a growth intercept model for interior balsam. B.C. Min. For., For. Pract. Br., Victoria, B.C. Unpubl rep.

that the fit may be poor above breast height age 50. However, a comparison of the curves to the data show that the fit is good, at least up to breast height age 150 (Figure 4). At site index 25 m, the coastal and interior models are similar. Little is known about the site types of the coastal plots because their ecosystems were not classified. Therefore, it is difficult to hypothesize on causes of the different height growth patterns of coastal and interior sites. One explanation may be that the low-productivity sites on the coast are nutrient-poor and dry and cannot support prolonged height growth.

The growth intercept models provide an opportunity to obtain good estimates of site index in juvenile stands of western redcedar. As with other growth intercept models, it is critical that accurate height and age measurements be taken to avoid large errors in site index estimates, particularly in young stands. No special procedures are required in growth intercept surveys for redcedar. However, unlike many other species, the

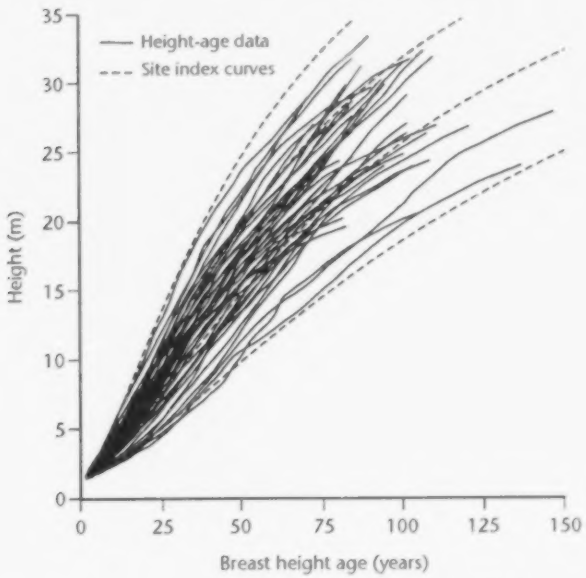

FIGURE 4 *Comparison of the fitted site index curves and the height-age data.*

breast height age cannot be determined by counting whorls.

A comparison of the relative accuracy in the estimated site indices from the site index and growth intercept models across a range of ages may be important when faced with a choice between models (Figure 5). In many cases, only one model will be applicable; for example, in very young (below breast height) stands, in stands with a large of amount of damage, or in stands for which ecosystem data are unavailable. However, if a choice must be made, the most accurate model should be chosen unless other factors need to be considered. The accuracy of the site index model is not graphed for older breast height ages because the accuracy estimates are based on too few data points to be meaningful. This graph shows that the growth

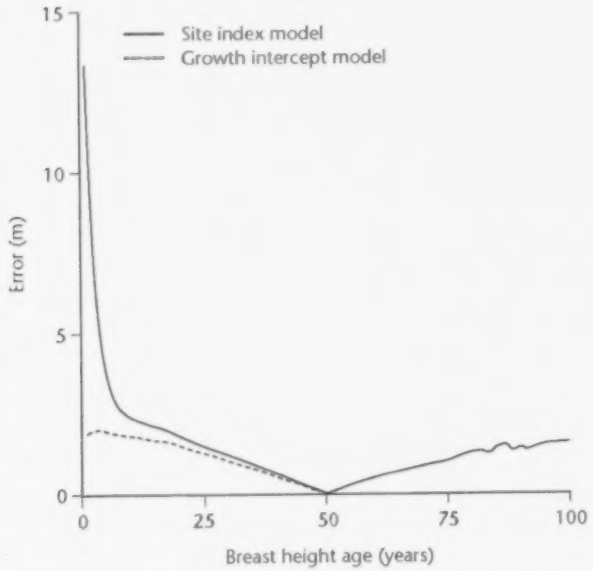

FIGURE 5 *Relative accuracy of the site index and growth intercept models.*

intercept models are best in stands up to breast height age 50 and that the site index model should be used in stands over breast height age 50. When the accuracy of a SIBEC model is available, it can be compared to that of the growth intercept and site index models shown in Figure 5.

CONCLUSION

A set of western redcedar stem analysis and ecological data was collected in the interior of British Columbia. Accurate site index, growth intercept, and years to breast height models were developed from these data. The site index and years to breast height models replace the coastal western redcedar models for applications in the interior of the province. To estimate site index, the growth intercept model is suggested for stands up to breast height age 50 and the site index model for stands older than breast height age 50.

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